Effects of mulch and planting methods on *Medicago ruthenica* seed yield and soil physical-chemical properties

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Abstract: *Medicago ruthenica* (L.) Trautv., a wild grass species, is commonly grown as a forage crop in arid and semi-arid areas of China. Herein, we explored mulch patterns and planting methods for optimizing *M. ruthenica* seed production in the loess plateau of the Gansu Province, China from 2017 to 2019. The experiments comprised of six treatments including (1) flat ground without mulch (F0, control); (2) flat ground with a transparent white 0.008 mm thick plastic film mulch (FP); (3) flat ground with 4500 kg/hm^2 straw mulch (FS); (4) furrow with 10 cm ridges (R0); (5) furrow with plastic film mulch (RP); and (6) furrow with straw mulch (RS). Results showed that the harvested seed yield of *M. ruthenica* was the highest under RP treatment, followed by FP and FS treatments. Soil moisture content from mid-May to mid-August in 2017 was the highest under RP and FP treatments, followed by RS and FS treatments. In 2018, soil moisture content was the highest under RS and FS treatments. In 2017 and 2018, soil temperature was the highest under FP and RP treatments, followed by F0 and R0 treatments. Total and available nitrogen, phosphorus, and potassium contents were the highest under RS and FS treatments, followed by RP and FP treatments. Comprehensive analysis result showed that surface mulch improved soil microenvironment and increased seed yield of *M. ruthenica*. Straw mulch also effectively recycled excess crop straw, thereby encouraging the sustainable development of agriculture in this area. In conclusion, FS treatment was considered the best mode for *M. ruthenica* seed production in this area.

Keywords: arid area; plastic film; straw mulch; soil moisture content; soil temperature; soil chemistry

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1 Introduction

Medicago ruthenica (L.) Trautv., a perennial herbaceous plant of Leguminosae, is a widely grown forage crop in arid and semi-arid areas due to its high potential yield and tolerance to drought and cold (Shu et al., 2018). Its ability to grow in barren environments makes it promising for forage cultivation and reseeding of natural grassland, thereby playing a substantial role in grassland animal husbandry and ecological restoration (Huang et al., 2007; Li et al., 2013; Xiao et al., 2018a). However, mature *M. ruthenica* plants exhibit natural seed dispersal, which hinders the large-scale collection of mature seeds for agricultural purposes. To date, *M. ruthenica* seed production and collection has received limited scientific attention (Li et al., 2006; Li and Shi, 2006). The difficulty in collecting *M. ruthenica* seeds prevents the possibility of large-scale propagation of this species; hence, it is important to research *M. ruthenica* seed production and collection.

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In recent years, due to the modification of Chinese agricultural planting structure, forage seed is not only important for the production and development of grassland industry, but also a key factor for forage production. Furthermore, continuous attention to ecological environment protection, animal husbandry development, and urban greening in China has increased the demand for excellent grass varieties and high-quality forage seeds (Shao et al., 2014). Additionally, such demands have revealed the problems associated with low yield and poor benefits of forage seed production in China.

Water is a major limiting factor for *M. ruthenica* seed production in arid and semi-arid areas because of low precipitation and high evaporation. Mulch can majorly maintain soil moisture and improve water utilization in arid and semi-arid areas. At the same time, mulch covers can reduce evaporation and compensate for inconsistent precipitation. In addition, mulch can also improve soil environment and considerably increase seed yield (Zhao et al., 2012; Chen et al., 2015; Yang et al., 2018). At present, water saving measures include film mulch, straw mulch, and the use of ridge and furrow (Han, 2018). Surface mulch with ridge and furrow treatment regulates soil temperature, soil moisture content, and air permeability, thereby supporting microbial communities and effectively promoting material transformation and nutrient decomposition in arid areas (Liu et al., 2014). Surface mulch with plastic film can promote soil organic carbon (SOC) and total nitrogen (TN) mineralization, and can effectively increase available nitrogen (AN), phosphorus (AP), and potassium (AK) contents in soil. However, soil water collected within the shallow layer under plastic mulch is absorbed by the crops from the lower layer when growing, which causes the upward movement of water from deep layer, thereby reducing deep layer water content (Zhou et al., 2012; Kader et al., 2017). In straw mulch, straw decomposes to produce organic compounds under favorable soil conditions. This, combined with rainwater seepage, leads to a gradual breakdown of mulch, increasing SOC and available nutrient contents. Thus, straw mulch can serve as an important source of soil organic matter (SOM) content (Tang, 2019). In a study of straw mulch treatment for wheat and maize, SOC and TN contents at 0–10 cm soil depth increased by 16.9% and 7.7%, respectively, compared with that of control treatment (Shao et al., 2016). However, in previous studies, it has been observed that plants absorb excess soil AN, AP, and AK during growth and development, decreasing available soil nutrients (Hu et al., 2012; Yin et al., 2016).

Longzhong Area is located in the middle of the Gansu Province, accounting for 16.8% area of the Gansu Province, China. The distribution of annual precipitation is irregular and varies considerably. Most precipitation occurs from July to September. Due to the concentrated rainfall in plant growth season, Longzhong Area is a typical rain-fed agriculture (Liu and Wang, 2018). However, the researches of effects of mulch treatments on *M. ruthenica* seed yield and soil nutrient contents are less concerned in the Longzhong Area (Luo et al., 2014). Our aims are to analyze the effects of different mulch treatments on *M. ruthenica* seed yield and soil physical-chemical properties in the arid Longzhong Area. The results might provide a theoretical basis for guiding forage cultivation and precision fertilization in the similar areas.

2 Materials and methods

2.1 Study site

The study site was located in the Longzhong Area, Gansu Province, China (35°58′N, 104°62′E) with an altitude of 2000 m a.s.l. The main soil type in this site is yellow soil, with average annual sunshine of 2409 h, average annual precipitation of 427 mm with extremely uneven distribution, and average annual evaporation of 1510 mm. The annual average temperature is 6.3℃, and average annual active accumulated temperatures ≥5.0℃ and ≥10.0℃ are 2782.5℃ and 2239.1℃, respectively. Temperature extremes ranged from −27.1℃ to 34.3℃, and the average annual frost-free period is 141 d (Liu and Wang, 2017). Soil pH is 7.0–8.2. SOM, TN, total phosphorous (TP), and total potassium (TK) contents are 47.81, 1.38, 1.10, and 8.36 g/kg, respectively.

Furthermore, AN, AP, and AK contents are 36.32, 7.37, and 159.89 mg/kg, respectively. The average monthly temperature and precipitation from 2017 to 2019 are shown in Figure 1.

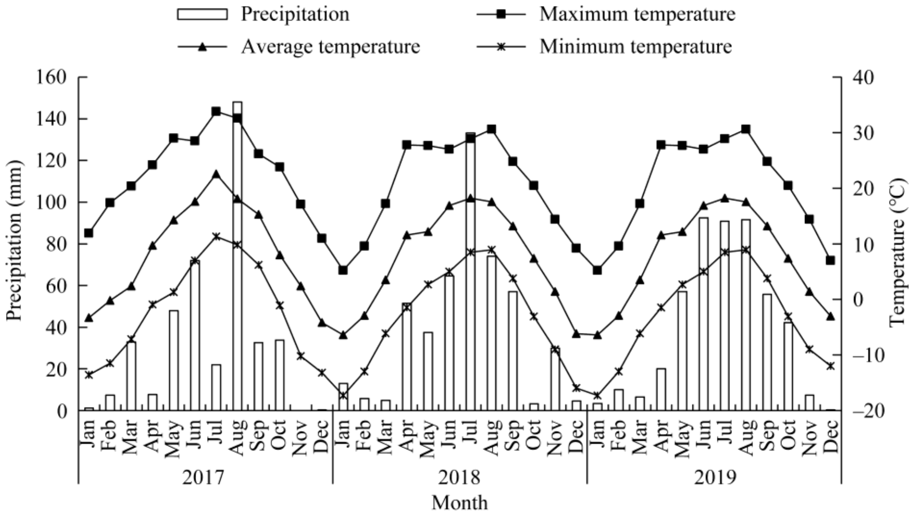


Fig. 1 Monthly temperature and precipitation in the study area from 2017 to 2019

2.2 Experimental design

The experiment comprised of six treatments, each with 30 cm row spacing: (1) flat ground without mulch (F0, control); (2) flat ground with a transparent white 0.008 mm thick plastic film mulch (FP); (3) flat ground with 4500 kg/hm^2 straw mulch (FS); (4) furrow with 10 cm ridge (R0); (5) furrow with plastic film mulch (RP); and (6) furrow with straw mulch (RS; Fig. 2). In the ridge and furrow design, plants were grown in the furrow, not on the ridge. The area of each cell was 2 m×5 m, and the treatment interval was 0.5 m. The treatment design was a random block, and was repeated thrice. We sown the seeds on 2 May, 2017, using the hole seeding method according to seedling emergence appropriate supplementation, or reduction in seedlings, at a depth of 2–3 cm, with 5–10 seeds per hole to ensure a survival rate of 3–5 per hole. The plant spacing was 10 cm, and the row spacing was 30 cm. Before sowing, *M. ruthenica* seeds were soaked in 98% concentrated sulfuric acid for 15 min, followed by washing with running water to break the hard outer cover.

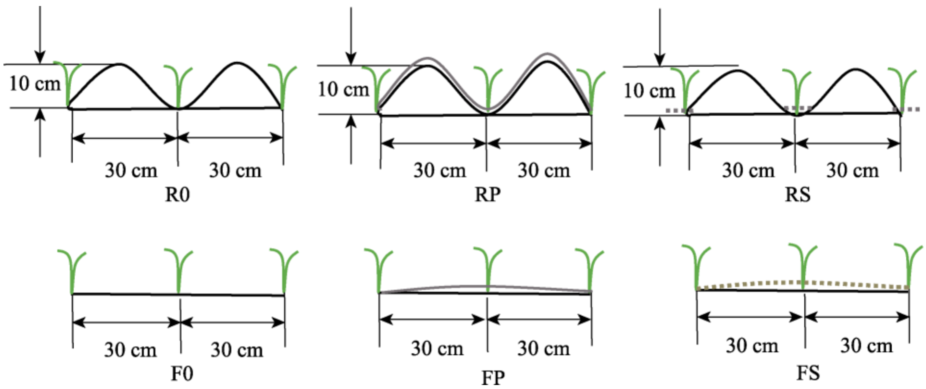


Fig. 2 Schematic diagram of *M. ruthenica* planting under different mulch treatments. Gray straight line refers to the transparent plastic film, and dotted line refers to the surface straw cover. R0, furrow with 10 cm ridge; RP, furrow with plastic film mulch; RS, furrow with straw mulch; F0, flat ground without mulch; FP, flat ground with a transparent white 0.008 mm thick plastic film mulch; FS, flat ground with 4500 kg/hm^2 straw mulch. The abbreviations are the same as the following figures.

2.3 Measurements

2.3.1 Performance seed yield

Performance seed yield (kg/hm^2) is calculated by Equation 1:

$$Y = P \times S \times W \times 10^{-2}, \tag{1}$$

where Y is the performance seed yield (kg/hm^2); P is the number of pods per unit area (m^2); S is the number of seeds per pod; and W is the thousand-seed weight (g) (Xiao et al., 2018b).

2.3.2 Actual seed yield

Due to the dispersal of the matured seeds, we selected a 1-m^2 sample area away from the side line of the treated sample to measure the actual seed yield in the seed maturity stage. This process was repeated thrice per treatment to calculate the average value.

2.3.3 Soil moisture content, soil bulk density, and soil porosity

Soil samples were collected once a month on a sunny day during the growing season of *M. ruthenica* (soil moisture content was collected from mid-May to mid-September in 2017 and 2018, while soil bulk density and soil porosity soil samples were collected from mid-May to mid-September in 2018 and 2019). Three soil profiles were assessed using the randomly dug soil from each treatment, and five soil samples were collected from the four 10 cm segments (0–10, 10–20, 20–30, 30–40, 40–50, 50–60, 60–70, and 70–80 cm) using a 5-cm diameter soil ring knife. Each cylindrical soil sample was loaded into a sample box and transferred to the laboratory. The samples were placed in an electric thermostatic air blowing drying oven (GZX-GF101-3-BS-II, Shanghai, China) and dried at 105℃ until a constant weight was obtained for measurements and subsequent calculations.

Soil moisture content is calculated by Equation 2:

$$M = \frac{M_2 - M_1}{M_1 - M_0} \times 100\,\%, \tag{2}$$

where M is the soil moisture content (%); M_2 is the mass of wet soil in the aluminum box (g); M_1 is the mass of dry soil in the aluminum box (g); and M_0 is the weight of an empty aluminum box dried to a constant weight (g) (Wilke, 2005).

Soil bulk density is calculated by Equation 3:

$$B = \frac{W_1 - W_0 \times (1 - M)}{V}, \tag{3}$$

where B is the soil bulk density (g/cm^3); W_1 is the total weight of ring knife and fresh soil (g); W_0 is the total weight of ring cutter (g); M is the soil moisture content (%); and V is the volume of soil core (100 cm^3).

Soil porosity is calculated by Equation 4:

$$P = 1 - \frac{B}{G} \times 100\%, \tag{4}$$

where P is the soil porosity (kPa); G is the specific gravity of soil fixed at 2.65 g/cm^3.

2.3.4 Soil temperature

Soil temperature was determined by selecting one sunny day in the middle of each month during the growing season. A curved tube geothermometer was used to measure temperature every 5 cm at a depth of 5–25 cm. Measurements were recorded every 2 h from 08:00 to 18:00 (LST), and each measurement was repeated thrice to obtain the average value (Zhou et al., 2017).

2.3.5 Soil compactness

Soil compactness was measured using a soil compactness meter (SC-900, spectrum, USA). Soil compactness was measured up to a thickness of 30 cm, and measurements were made 20 times for

each plot.

2.3.6 Soil nutrients

Soil nutrients change gradually; hence, they were collected only once during mid-October between 2018 and 2019. Soils cores were collected as described in Section 2.3.3 using a 3.5-cm diameter soil auger. After removing the visible debris, we placed samples into zip-top bags and transported to the laboratory. After natural drying, we passed each sample through 0.25- and 1.00-mm soil sieves for soil nutrient analysis (Hou et al., 2018).

According to the methods described by Bao (2000), we determined SOM content using the potassium dichromate titration. Soil TN content was determined using the Kjeldahl method. Soil TP content was determined using the molybdenum blue method with an ultraviolet-visible spectrophotometer (SP-756P, Shanghai Guangpu Instuments Co., Ltd., China). Soil TK content was determined using the NaOH melt-flame photometry. Soil AN content was determined using the alkali-hydrolyzed diffusion method. Soil AP content was determined using the 0.5 mol/L $NaHCO_3$-molybdenum-antimony resistance colorimetric method. Soil AK content was extracted using the NH_4OAC with flame photometry.

2.4 Statistical analysis

Microsoft excel 2010 was used for data collation and visualization, and all values were expressed as mean±standard errors (SE). Compared means in SPSS v.22.0 (SPSS Inc., Chicago, IL, USA) was used for conducting a one-way analysis of variance on the experimental data. Generalized lineal model (GLM) was used to analyze the effects of planting years and different mulch treatments on *M. ruthenica* seed production and soil properties. Significance was determined at $P<0.05$ level. The Duncan method was used for multiple comparison analysis.

3 Results

3.1 Seed yield of *M. ruthenica*

The performance and actual seed yields of *M. ruthenica* from 2017 to 2019 were the highest under RP treatment, and the lowest under F0 treatment. Seed yield of *M. ruthenica* under FS treatment was always higher than that of RS treatment. Furthermore, plastic mulch had the highest seed yield, followed by straw mulch (Fig. 3). Seed yield under R0 and F0 treatments were significantly lower than those of other treatments ($P<0.05$) from 2017 to 2018. There were no significant differences between RP and FP, between RS and FS, and between R0 and F0 treatments for the performance and actual seed yields ($P>0.05$). The average actual seed yield of *M. ruthenica* during 2017–2019 was 203–279 kg/hm^2 (Fig. 3b).

Under the same treatment, the performance seed yield of *M. ruthenica* in 2018 was significantly higher than those in 2017 and 2019 ($P<0.05$), with no significant difference observed between 2017 and 2019 for the same treatment (Fig. 3a). The actual seed yield of all

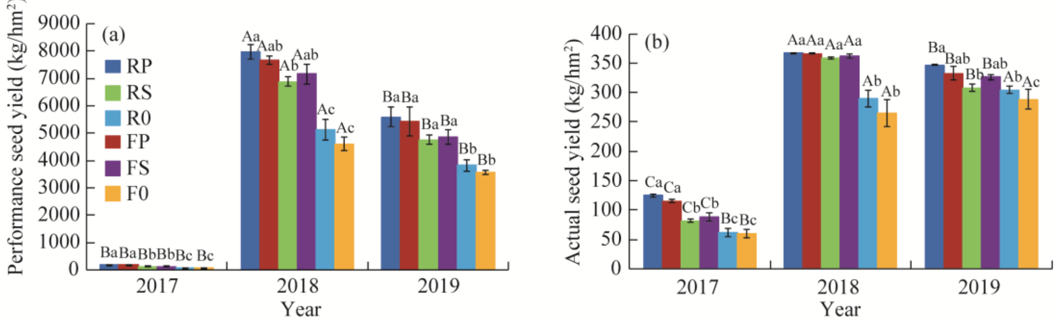


Fig. 3 Effects of mulch and planting methods of *M. ruthenica* on performance (a) and actual seed yields (b) from 2017 to 2019. Different uppercase letters within the same treatment indicate significant differences among different years at $P<0.05$ level; Different lowercase letters within the same year indicate significant differences among different treatments at $P<0.05$ level.

treatments in 2018 was significantly higher than that in 2017, and there was no significant difference observed between 2018 and 2019 under R0 and F0 treatments (P>0.05; Fig. 3b).

3.2 Effect of mulch and planting methods on soil physical properties

3.2.1 Soil moisture content

In 2017, from mid-May to mid-August, the order of soil moisture content for each depth under different mulch treatments was R (furrow)>F (flat ground), P (plastic film mulch)>S (straw mulch)>0 (no mulch), and soil moisture content values for 0–10 and 10–20 cm depths in each treatment were slightly higher than those of other soil depths (Fig. 4). However, in mid-September, soil moisture contents of corresponding soil depth under RS and FS treatments were higher than those of RP and FP treatments. Soil moisture contents under R0 and F0 treatments were significantly lower than those of other treatments (P<0.05).

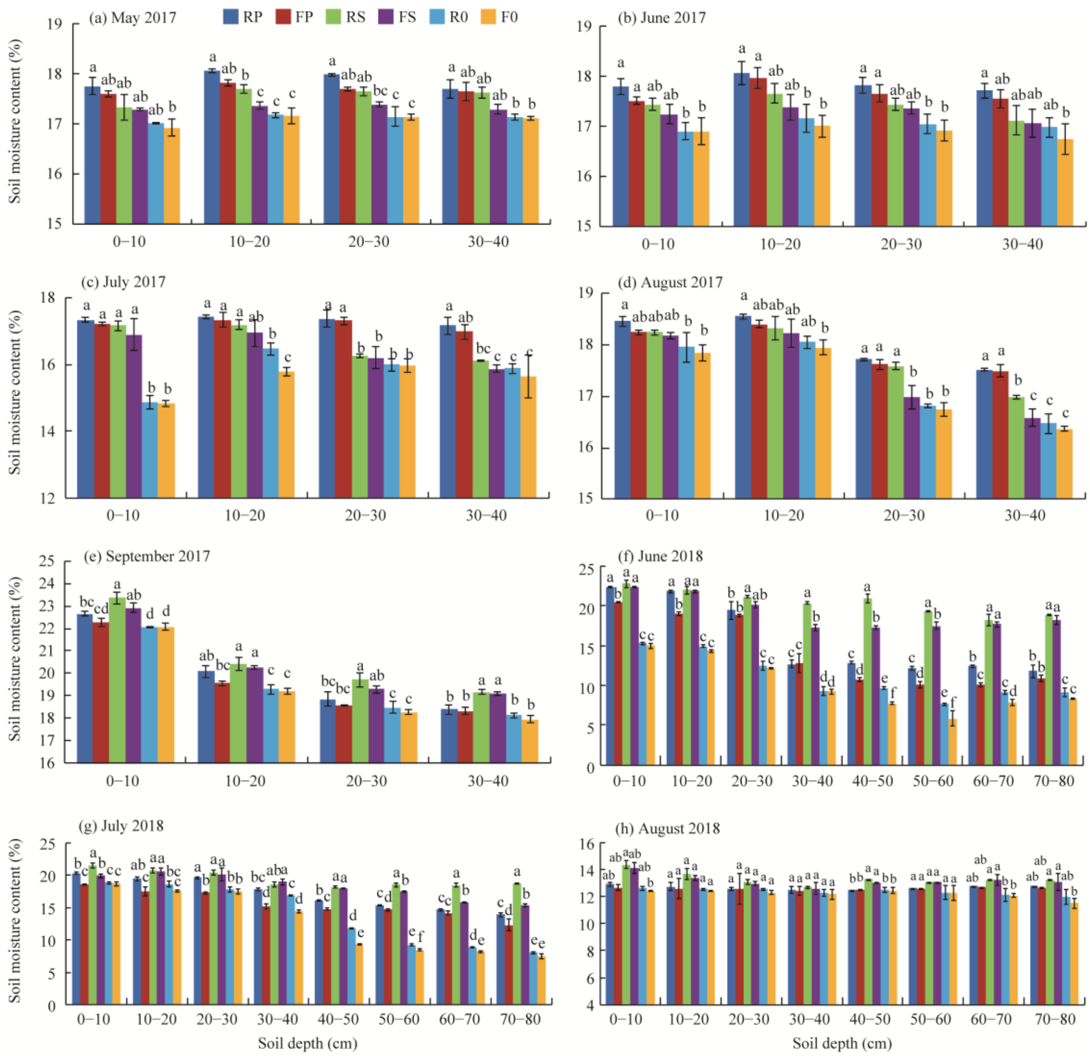


Fig. 4 Effects of mulch and planting methods of *M. ruthenica* on soil moisture content in 2017 and 2018. Different lowercase letters within same soil depth indicate significant differences among different treatments at P<0.05 level. (a), May 2017; (b), June 2017; (c), July 2017; (d), August 2017; (e), September 2017; (f), June 2018; (g), July 2018; (h), August 2018.

In 2018, from mid-June to mid-August, soil moisture content for each soil depth under different mulch treatments was the highest under RS treatment and the lowest under F0 treatment (Fig. 4).

Under RP treatment, soil moisture content was always higher than that of FP treatment. Moreover, plastic mulch treatment was more effective than straw mulch. Soil moisture content of each treatment showed a decreasing trend with increasing in soil depths.

From mid-June to mid-July, soil moisture content under RS and FS treatments were significantly higher than that of F0 treatment at 0–80 cm soil depth, whereas soil moisture content at 40–80 cm depth under RS and FS treatments were significantly higher than those of other treatments (P<0.05).

3.2.2 Soil temperature

From mid-May to mid-September in 2017 and 2018, the average daily soil temperature increased rapidly with plastic mulch treatments, followed by control and straw mulch treatments (Fig. 5). Soil temperature for each treatment exhibited a significant daily change at 5–10 cm soil depth, but it did not vary significantly at 10–25 cm depth. Average soil temperature of each treatment presented an inverse trend with soil depths. From 08:00 to 18:00 on a given day, soil temperature for each depth under each treatment first increased and then decreased.

In mid-May, mid-June, and mid-September of 2017, soil temperature for each treatment reached the highest at 14:00, and then gradually decreased. Whereas, in mid-July, mid-August of 2017, mid-June, mid-July, and mid-August of 2018, soil temperature for each treatment peaked at 16:00.

From mid-May to mid-September of 2017, soil temperature under RP treatment at 08:00 was the highest, followed by FP treatment (Fig. 5). At 5 cm soil depth, from mid-May to mid-August, soil temperatures under RP and FP treatments were significantly higher than those of other treatments (P<0.05); and soil temperature under FP treatment was significantly higher than that of FP treatment at 10:00, 12:00, 14:00, 16:00, and 18:00. In mid-May, mid-June, and mid-August, soil temperature under RS treatment was significantly lower than those of RP and FP treatments (P<0.05). In mid-September, at 5 cm soil depth, no significant difference was observed in soil temperature between RP and FP treatments (P>0.05).

3.2.3 Soil bulk density, soil porosity, and soil compactness

In 2018 and 2019, soil bulk density for each soil depth under different treatments was the lowest for straw mulch and the highest for control (Fig. 6a). Soil bulk density at 0–20 cm depth was the lowest under RP, FP, RS, and FS treatments. Analysis of variance showed that growth year did not significantly affect soil bulk density. Soil bulk density reached an extremely significant level at 0–20 cm depth (P<0.01).

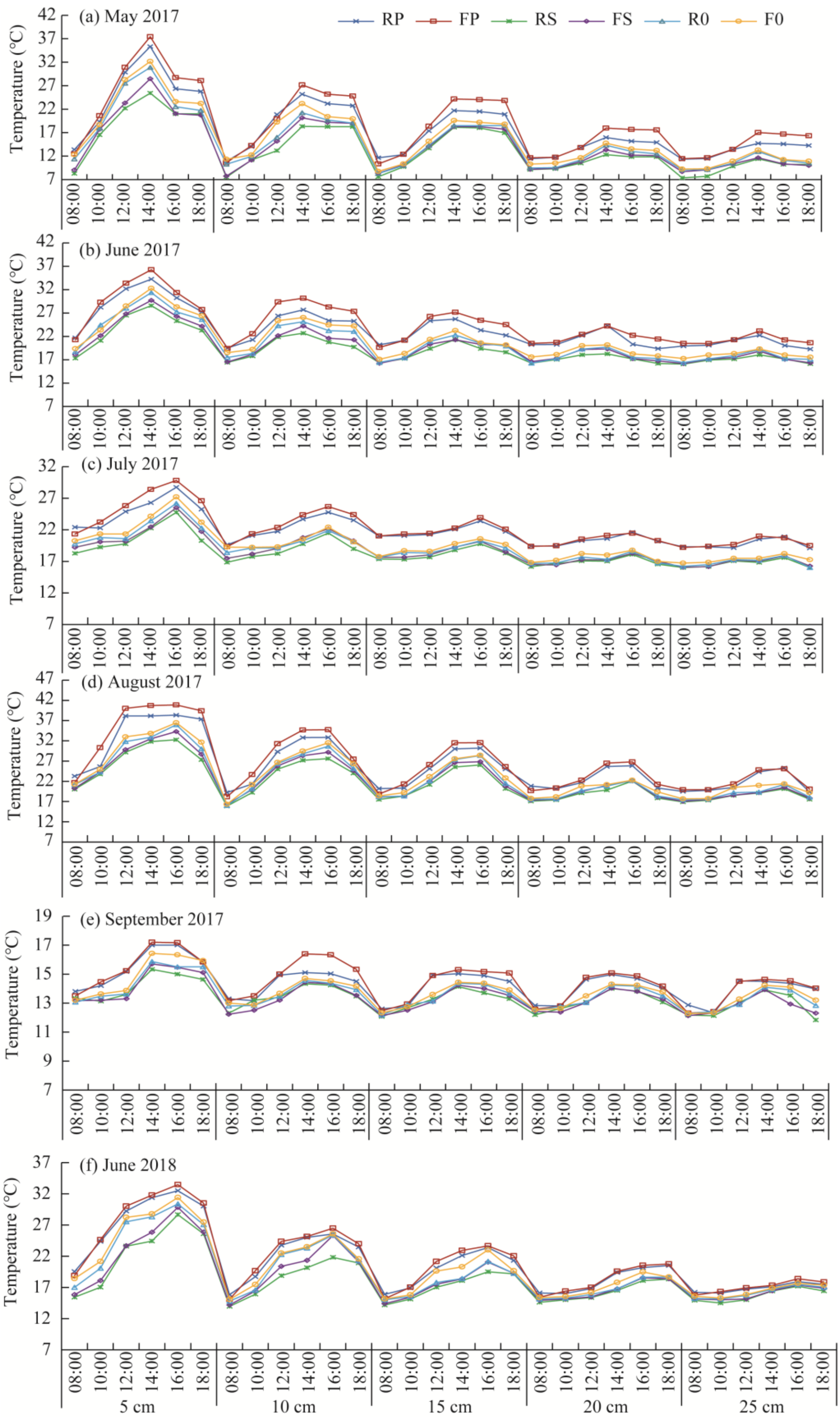
In 2018 and 2019, soil porosity under FS treatment was the highest and was the lowest under R0 treatment (Fig. 6b). Furthermore, soil porosity was always higher under flat ground than furrow treatment. Soil porosity for each treatment was the highest at 0–10 and 10–20 cm soil depths, then the values of soil porosity decreased with increasing soil depths. Analysis of variance showed that growth year displayed no significant effect on soil porosity. Effects of treatment on soil porosity at 0–10 and 10–20 cm soil depths reached an extremely significant level (P<0.01).

In 2018 and 2019, straw mulch treatments exhibited the lowest soil compactness, and control treatment had the highest values (Fig. 6c). Soil compactness of all treatments increased and then decreased with soil depths, with the maximum values at 10–20 cm soil depth and a variation range of 110–152 kPa. Analysis of variance showed that growth year did not significantly affect soil compactness. Treatment did significantly affect soil compactness (P<0.01) at 0–10 cm soil depth. Interaction between growth year and treatment had no significant effect on soil bulk density, soil porosity, and soil compactness (P>0.05).

3.3 Effects of mulch and planting methods on soil chemical properties

3.3.1 SOM, soil TN, and AN

In 2018 and 2019, SOM content under RS treatment was the highest, and was the lowest under FP treatment; SOM under straw mulch was higher than that of no mulch, and was the lowest for plastic film mulch (S>0>P; Fig. 7a and b). Compared with control treatment, straw mulch increased SOM content, and plastic film mulch reduced it. SOM content of each treatment


(a) May 2017
(b) June 2017
(c) July 2017
(d) August 2017
(e) September 2017
(f) June 2018
RP
FP
RS
FS
R0
F0
Temperature (°C)
08:00
10:00
12:00
14:00
16:00
18:00
5 cm
10 cm
15 cm
20 cm
25 cm

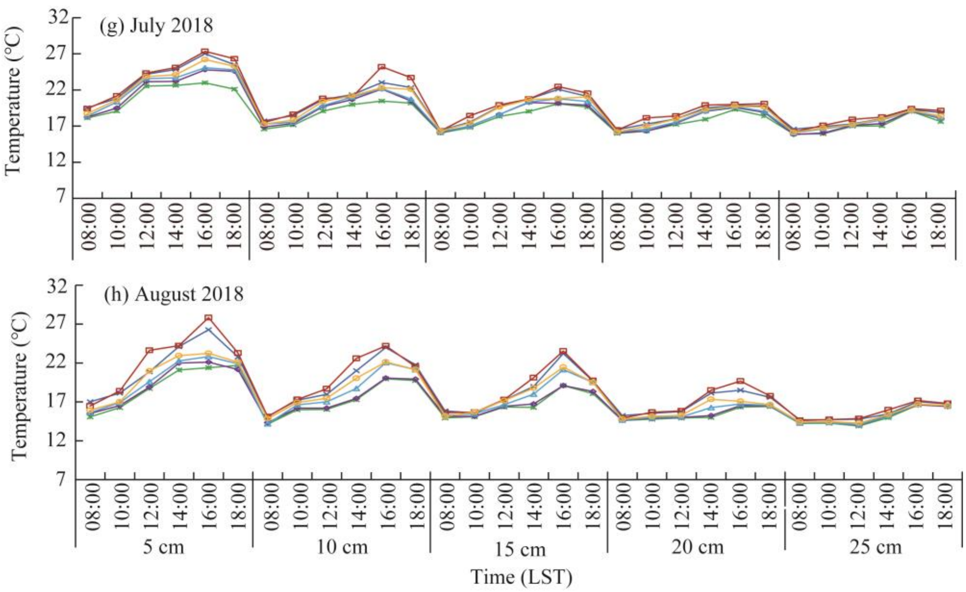


Fig. 5 Effects of mulch and planting methods of *M. ruthenica* on soil temperature in 2017 (a–e) and 2018 (f–h)

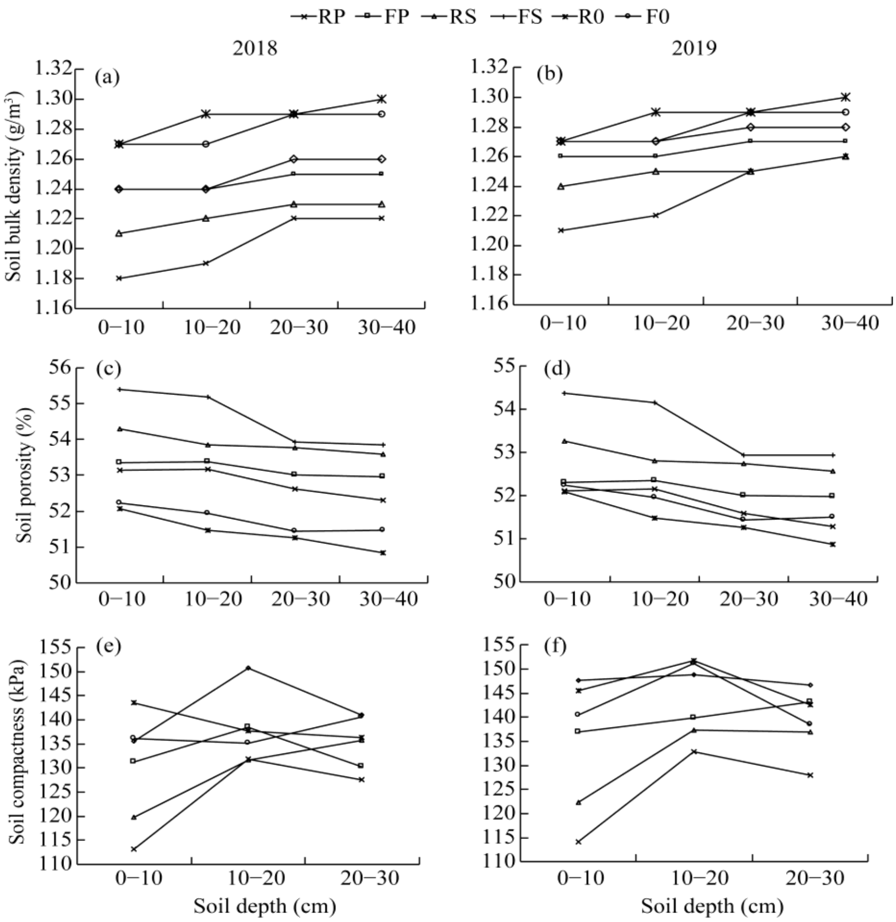


Fig. 6 Effects of mulch and planting methods of *M. ruthenica* on soil bulk density (a and b), porosity (c and d), and compactness (e and f) in 2018 and 2019

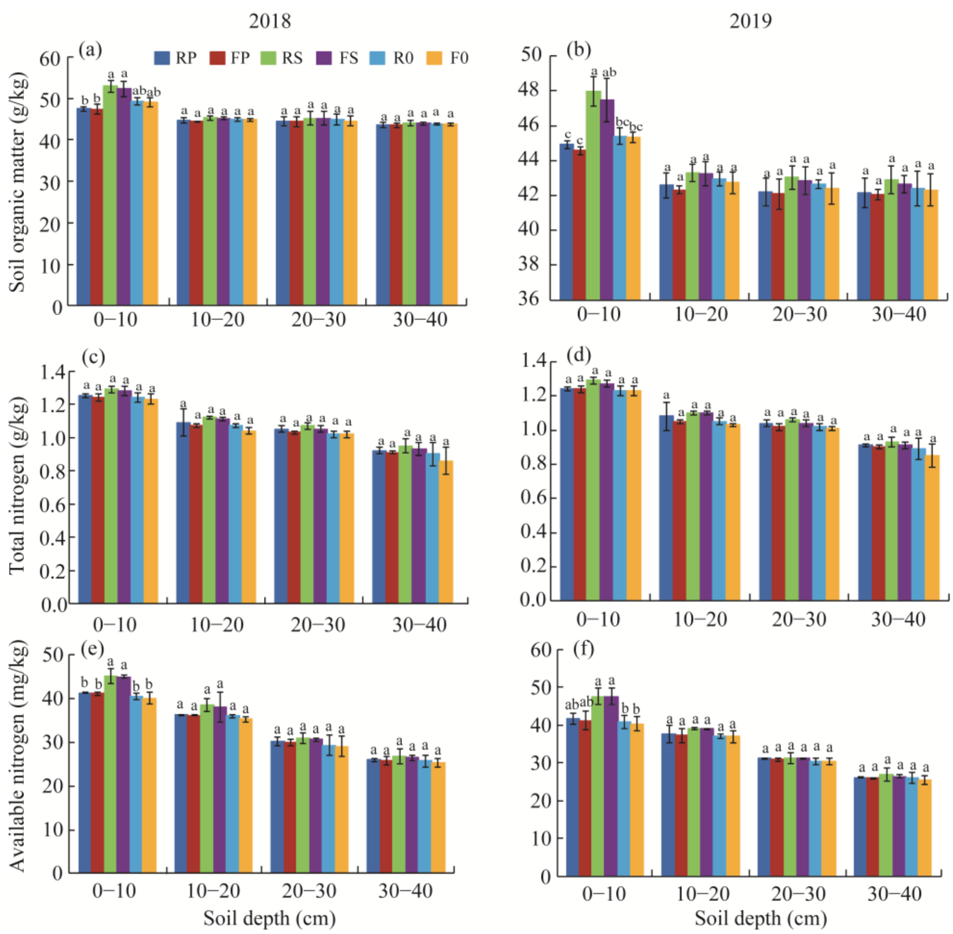


Fig. 7 Effects of mulch and planting methods of *M. ruthenica* on soil organic matter (a and b), total nitrogen (c and d), and available nitrogen (e and f) in 2018 and 2019. Different lowercase letters within the same soil depth indicate significant differences among different treatments at *P*<0.05 level.

decreased with soil depths. In 2018 and 2019, SOM content at 0–10 cm soil depth under RS and FS treatments was significantly higher than those of RP and FP treatments (*P*<0.05). No significant difference was observed in SOM content among different treatments at 10–40 cm soil depth (*P*>0.05). Growth year significantly influenced SOM content (*P*<0.01). Effect of treatment on SOM content at 0–10 cm soil depth was extremely significant (*P*<0.01).

In 2018 and 2019, soil TN content for each soil depth was the highest under straw mulch, followed by plastic film mulch (S>P), and the lowest soil TN content was observed for no mulch treatment (Fig. 7c and d). TN content presented an inverse trend with soil depths. At 0–40 cm soil depth, no significant difference was observed in soil TN content among different treatments in 2018 and 2019 (*P*>0.05). Analysis of variance showed that growth year, treatment, and their interaction did not significantly affect soil TN content (*P*>0.05).

In 2018 and 2019, soil AN content for each treatment presented a decreasing trend with increasing soil depths (Fig. 7e and f). In 2019, soil AN contents under RS and FS treatments were significantly higher than that of F0 treatment (*P*<0.05), but no significant difference was observed among other treatments. In 2018 and 2019, no significant difference was observed in soil AN content among treatments at 10–40 cm soil depth (*P*>0.05). Analysis of variance showed that growth year did not significantly affect the variation of soil AN content. Treatment extremely significantly affected soil AN content at 0–10 cm soil depth (*P*<0.01).

3.3.2 Soil TP, AP, TK, and AK

In 2018 and 2019, soil TP content for each soil depth was the highest for straw mulch, followed by plastic film mulch (S>P), soil TP content decreased with increasing in soil depths (Fig. 8a and b). Analysis of variance showed that growth year did not significantly affect soil TP content, whereas treatment significantly affected soil TP content at 0–10 and 10–20 cm soil depths (P<0.05).

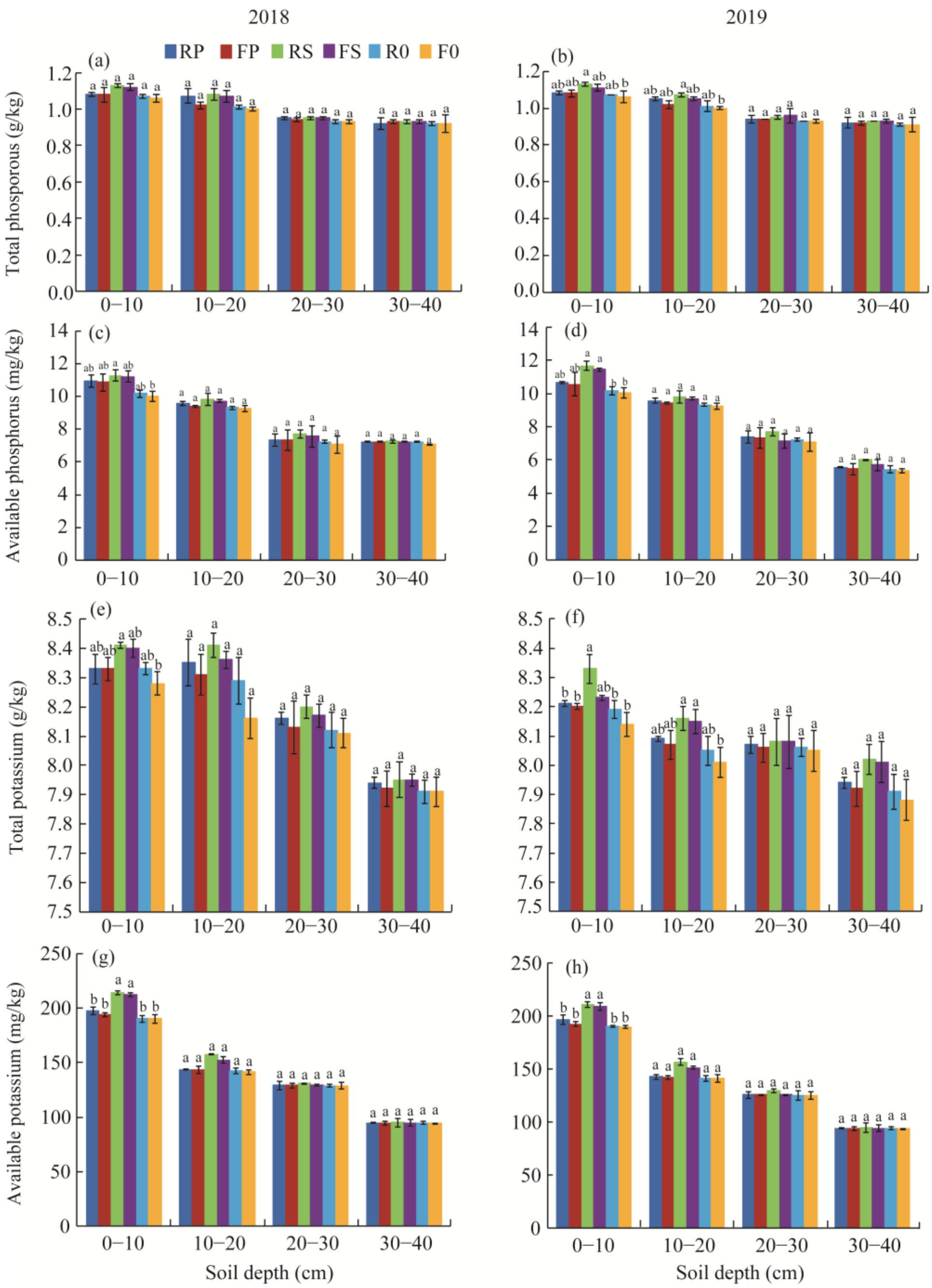


Fig. 8 Effects of mulch and planting methods of *M. ruthenica* on soil total phosphorous (a and b), available phosphorus (c and d), total potassium (e and f), and available potassium (g and h) in 2018 and 2019. Different lowercase letters within the same soil depth indicate significant differences among different treatments at P<0.05 level.

In 2018 and 2019, soil AP content for each soil depth was the highest under RS treatment and the lowest under F0 treatment (Fig. 8c and d). Soil AP content under straw mulch was higher than that of plastic film mulch. In 2018, soil AP content under RS treatment at 0–10 cm soil depth was significantly higher than that of F0 treatment ($P<0.05$). In 2019, soil AP contents under RS and FS treatments were significantly higher than those of R0 and F0 treatments ($P<0.05$). There was no significant difference among treatments at other soil depths ($P>0.05$). Growth year did not significantly affect soil AP content, whereas treatment extremely significantly affected soil AP content at 0–10 cm soil depth ($P<0.01$).

In 2018 and 2019, soil TK content for each soil depth was the highest under straw mulch, followed by plastic film mulch. Soil TK content presented a decreasing trend with increasing soil depths (Fig. 8e and f). Effect of growth year significantly affected soil TK content at 0–10 cm and 10–20 cm soil depths ($P<0.01$), and treatment significantly affected soil TK content at 0–10 cm soil depth ($P<0.01$).

In 2018 and 2019, soil AK contents under RS and FS treatments were significantly higher at 0–10 and 10–20 cm soil depths than those of other treatments ($P<0.05$; Fig. 8g and h). There were no significant differences in soil AK content at 20–30 and 30–40 cm soil depths ($P>0.05$). Growth year did not significantly affect soil AK content. Effects of treatment at 0–10 cm and 10–20 cm soil depths were extremely significant ($P<0.01$). Interaction between growth year and treatment did not significantly affect soil TP, AP, TK, and AK contents ($P>0.05$).

4 Discussion

4.1 Effects of mulch and planting methods on *M. ruthenica* seed yield

We found that seed yield of *M. ruthenica* over the three-year experiment was the highest under plastic film mulch and the lowest under no mulch. Since the surface cover treatment and the fact that ridge and furrow planting methods resulted in the accumulation of natural rainfall, the seed yield may have increased by improving the water utilization rate of the plants. The ridge funnels the rainfall into furrow, and in the early stage of crop growth, the water retention effect of plastic film mulch was higher than that of straw mulch (Fig. 4). Studies have shown that increased temperature and water availability are associated with increased crop growth under mulch conditions. Under the effect of increasing temperature and promoting water consumption, mulch cultivation can expand crop growth periods and increase dry weight per plant (Li et al., 2018; Chen et al., 2019). Therefore, seed yield of *M. ruthenica* treated with plastic mulch was higher than that of straw mulch. In the first year of this study (2017), plastic mulch resulted in the highest soil moisture content (Fig. 4) and soil temperature (Fig. 5), which explains the result of the highest seed yield under FP and RP treatments. Additionally, *M. ruthenica* seed yield was the highest in the second year (2018).

In this study, an enormous gap was observed between performance seed yield and actual seed yield. Results showed that potential seed yield of forage crops is extremely high, but actual seed yield is extremely low, with a gap of approximately 12%–20% (Han et al., 1996). Additionally, the splitting rate of *M. ruthenica* is 93% when the seeds are fully mature, with a relatively high proportion of splitting pods (Li et al., 2006). During the harvesting process in the present study, seed pod splitting and maturity were inconsistent, resulting in substantial loss and a discrepancy between performance and actual seed yields.

All mulch treatments displayed desirable effects on soil microenvironment compared with that of control, mainly by increasing soil moisture content and nutrient content. Although plastic film mulch treatment was associated with high seed yield, soil moisture content, and temperature, plastic film is remained in the soil and degraded slowly, which is detrimental to the emergence and normal growth of crops (Yan et al., 2006). Plastic film is potentially detrimental to soil physical and chemical properties, including the white pollution caused by film residue, which has become a source of soil pollution (Qi et al., 2020; Xu et al., 2020). Straw mulch presented similar,

if not equal, effects on seed field and soil properties when compared with that of plastic, and in certain cases resulted in higher soil nutrient contents. Therefore, for the sustainable development of *M. ruthenica* in the arid Longzhong Area, straw mulch method should be prioritized.

4.2 Effects of mulch and planting methods on soil physical properties

4.2.1 Soil moisture content

In this study, both plastic film and straw mulch effectively increased soil moisture content. In 2017, RP and FP treatments resulted in the highest soil moisture content, followed by RS and FS treatments. The higher soil moisture content for ridge and furrow treatment instead of flat groud method may have been due to the fact that ridge planting effectively collects rainfall and shelters the growth area from wind evaporation, thereby improving water retention compared with that of flat ground method. Soil moisture content and seed yield of *M. ruthenica* treated with plastic film in 2017 were higher than those of other treatments. Plastic film mulch inhibits soil moisture evaporation, creating internal water circulation (Zhou et al., 2009). Thus, the circulation promotes soil water movement and accumulation from the deeper depths to the surface, and improves water retention (Liang et al., 1990). In this study, soil moisture content of straw mulch was higher than that of plastic film mulch in 2018. Straw mulch inhibited soil water evaporation and ensured that water demand of *M. ruthenica* is fulfilled in the later growth period, thus promoting seed production. In addition, the roughness of straw covering surface can effectively intercept rainfall, decrease surface runoff, and allow water to effectively infiltrate the soil, thus increasing soil moisture content (Li et al., 2013).

Due to the high soil evaporation that occurred in the study area, soil moisture content first increased and then decreased during the growth period of *M. ruthenica* (Peng et al., 2018). Moreover, cool weather and increased rainfall occurred in mid-September 2017 (Fig. 4), soil moisture content presented a decreasing trend. We found that soil moisture contents under RS and FS treatments were higher than those of RP and FP treatments, and soil moisture content under plastic film mulch decreased with increasing soil depths. Therefore, we can conclude that the effects of plastic film mulch on increasing soil temperature and moisture were better than that of straw mulch, thus significantly improving the growth of *M. ruthenica* in 2017. However, rapid growth of *M. ruthenica* consumes more soil moisture, causing dehydration in the later growth period (Lu et al., 2016). Simultaneously, plastic film mulch encourages water to move upward from deeper soil depths, resulting in the depletion of soil moisture at deeper depths. Therefore, plastic mulch is not conducive to the long-term sustainable development of *M. ruthenica* (Zaongo et al., 1997; Li et al., 1999).

4.2.2 Soil temperature

Soil temperature directly affects the development of plants and the emergence of seeds (Peng et al., 2018), and can be influenced by land cover materials and planting methods. In this study, the daily soil temperature of plastic film mulch was higher than that of straw mulch, which suggests that plastic film can effectively absorb solar energy and transmit heat into the soil surface. When air temperature drops, the retained heat at the lower soil depths is distributed toward the surface. Plastic mulch traps this heat at the surface, effectively providing thermal insulation (Chen, 2012; Jiang et al., 2016). Thermal insulation effect of plastic film mulch benefited the emergence of *M. ruthenica* seedlings, which was important for the growth and development of *M. ruthenica* in the later growth stage. Straw mulch also delays the emission of soil heat into the atmosphere and effectively prevents daily variations in soil temperature, thereby promoting the growth and development of root and stem system, which increases the seed yield of *M. ruthenica* (Fig. 3; Tang, 2019).

4.2.3 Soil bulk density, soil porosity, and soil compactness

Soil bulk density indirectly reflects the growth of crop roots and SOM accumulation. The lower the soil bulk density, the looser the soil. Soil porosity is also important for the growth of crop

roots, because it controls soil moisture, fertility, aeration, and heat (Wang et al., 2015; Li et al., 2019). We found that soil bulk density and soil compactness decreased after mulched by plastic film and straw, whereas soil porosity increased, indicating that surface mulch effectively improved soil structure. Moreover, soil bulk density and soil compactness at 0–20 cm soil depth under all mulch treatments were significantly lower than those under no mulch treatment, and soil bulk density of furrow and ridge treatment was higher than that of flat ground treatment. These results were associated with improved soil moisture content and soil temperature conditions. Under mulch treatment, rainfall directly falling on the ground is blocked, preventing compaction and promoting loose soil structure. However, Wang et al. (2015) found that during heavy rain, water collected in furrow eventually increases soil compactness and soil bulk density, and decreases soil porosity. In this study, soil bulk density under FS treatment was significantly lower than those of R0 and F0 treatments, which is likely attributed to reduced soil porosity caused by the long-term surface mulch. Straw mulch benefits the formation of soil aggregate structure and porosity, and is conducive to promoting proper growth and spatial distribution of plant roots (Bodner et al., 2015; Liao et al., 2021). Therefore, straw mulch can be used to create an isolated buffer zone for reducing soil bulk density and soil compactness, and increasing soil porosity (Mulumba and Lal, 2008; Xu et al., 2017).

4.3 Effects of mulch and planting methods on soil chemical properties

In this study, soil nutrient contents increased under all mulch treatments compared with control, confirming that mulch effectively improved soil fertility and ultimately promoted the crop growth (Dong et al., 2017). Moreover, SOM content under straw mulch was higher than that of plastic film mulch. The maintenance of soil moisture and temperature by mulch accelerates the decay and decomposition of straw, releasing organic particles that infiltrate soil and increase SOM at shallow zones (Akhtar et al., 2018). Meanwhile, surface mulch, ridge and furrow treatments improved soil microenvironment. *M. ruthenica* might use soil fertility by accelerating the conversion and utilization of soil nutrients. As *M. ruthenica* absorb nutrients from the soil, SOM content decreased with the increase of mineralization without additional fertilization, but leguminous forage rhizobia nitrogen fixation, in the process of leguminous plant growth can provide the required nitrogen nutrients, thereby reducing the use of nitrogen in the soil. Thus, planting legume forage did not significantly affect TN content in the soil. Meanwhile, nutrient contents decrease over time without additional fertilization, in particular, plants under plastic film mulch consume more nutrients than they do under other treatments due to fast growth in the early growth stage, which reduces soil fertility in the later growth stage (Pu et al., 2006). Therefore, successive years of plastic film mulch could eventually exhaust soil nutrients, which is not conducive to maintaining soil fertility or sustainable agriculture.

5 Conclusions

In this study, we found that performance and actual seed yields of *M. ruthenica* were the highest for plastic film mulch, followed by straw mulch. Soil moisture content in the first year of planting *M. ruthenica* was the highest under RP and FP treatments, followed by RS and FS treatments. While, in the second year, soil moisture content under straw mulch was higher than those of other treatments. Soil temperature was the highest under FP and RP treatments, followed by F0 and R0 treatments. Soil nutrient contents were the highest under RS and FS treatments, and generally deceased with soil depths. Meanwhile, mulch had a negligible effect on soil total nutrient contents, but significantly affected available nutrient contents. All treatments improved shallow soil physical-chemical properties as compared with that of control, and straw mulch presented the best effect. Comprehensive data analysis demonstrated that straw mulch was preferred to produce *M. ruthenica* seeds in the Longzhong Area and other similar areas with appropriate potassium fertilizer and phosphate fertilizer supplement.

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